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Ten Year-Environmental Test of Glass Fiber/Epoxy Pressure Vessels

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SUMMARY

By the beginning of the 1970's composite pressure vessels had received a significant amount of development effort, and applications were beginning to be investigated. One of the first applications grew out of NASA Johnson Space Center efforts to develop a superior emergency breathing system for firemen. While the new breathing system provided improved wearer comfort and an improved mask and regulator, the primary feature was low weight which was achieved by using a glass fiber reinforced aluminum pressure vessel. Part of the development effort was to evaluate the long term performance of the pressure vessel and as a consequence, NASA Johnson procured some 30 bottles for a test program. These bottles were then provided to NASA Lewis Research Center where they were maintained in an outdoor environment in a pressurized condition for a period of up to 10 yr. During this period, bottles were periodically subjected to cyclic and burst testing. There was no protective coating applied to the fiberglass/epoxy composite, and significant loss in strength did occur as a result of the environment. Similar bottles stored indoors showed little, if any, degradation. This report contains a description of the pressure vessels, a discussion of the test program, data for each bottle, and appropriate plots, comparisons, and conclusions.

INTRODUCTION

During the period from 1964 through 1974, Lewis Research Center conducted a number of technology programs to develop lightweight pressure vessels for spacecraft applications. Aerojet General Corporation, Arde, Inc., Boeing Aerospace, Douglas Aircraft, Grumman Aerospace, Martin Marietta, and Structural Composites Industries, under contract to NASA Lewis participated in the program which emphasized cryogenic applications; typically low pressure, large diameter, liquid hydrogen tanks, and high pressure, small diameter gaseous helium tanks which would operate at liquid hydrogen temperature. As a result of this effort, two distinctly different design concepts evolved (ref. 1). The first concept used a filament wound composite structural shell with a thin nonload bearing metal liner whose only purpose was to prevent leakage of the contained fluid. The second concept combined the structural properties of a liner, which both contained the fluid and carried a significant portion of the pressure load, with the structural capabilities of the overwrapped composite. While the first concept has not yet been used in applied systems, the second concept, which is defined as the load-sharing liner concept, is currently in use for a number of aerospace and commercial pressure vessels, most of which use a high performance Kevlar fiber as the composite overwrap. Examples of such applications are the pressurization bottles for the Boeing aircraft escape slides; nitrogen, oxygen, and helium bottles on the Space Shuttle; and helium bottles on the Centaur. The most widespread land based application is for air bottles in breathing systems such as firemen's backpacks and SCUBA equipment. In

fact, the land based applications were the initial users of the composite pressure vessel load sharing liner concept.

In the early 1970's, NASA Johnson Space Center, with their experience in life support systems, recognized a need for a modern emergency breathing system and funded a program with Scott Aviation to improve on the weight, comfort, and safety of commercially available, open loop, compressed air, backpack breathing systems. An extensive engineering study was conducted to determine the optimum concept. Although both open and closed loop systems were considered, an open loop system was selected due to the simplicity of maintenance, use of air rather than oxygen, and wider range of operational capability. The resulting open loop system featured extra high pressure (4000 psi as opposed to commercial systems at 2250 psi), a redesigned mask, a new harness and frame assembly, and a light-weight pressure vessel. Weight was reduced from 33 to 20 lb for a 30 min "rated" duration system and 10 of the 13 lb weight savings was attributable to the structural efficiency of the composite pressure vessel design. A number of these systems were then manufactured and placed in fire department services in New York City, Houston, and Los Angeles. Assessment of performance was made after 1 yr of trials (ref. 2), and, in general, the system was found to be very successful. Although it was several years before all of the improved components found widespread use in commercially available systems, the acceptance of the composite pressure vessels was immediate and, in one form or another, they quickly became a part of the product line of various breathing system manufacturers.

As part of the Scott Aviation program, burst tests, drop tests, overheating tests, gunfire tests, and fatigue tests were conducted to prove the pressure vessel design. NASA Johnson reported on these efforts and concluded their basic task in 1972. However, one part of the activity was not concluded until recently. In order to obtain long term environmental data on fiberglass composites and overwrapped pressure vessels, NASA Johnson requested NASA Lewis Research Center to conduct an extended outdoor exposure test of the composite pressure vessels from the fireman's breathing system program. NASA Lewis was eager to comply because the technology used in the development of the vessels was an extension of the NASA Lewis program, and the data to be obtained would add directly to the materials and design base for composite pressure vessels. Also, facilities to perform long term environmental tests and high pressure cyclic and burst tests were both available at NASA Lewis. This report is a description of the long term environmental tests and a discussion of the resulting data from burst and cyclic testing of the NASA Johnson pressure vessels over a 10 yr period from 1974 to 1984.

Description of Pressure Vessels Tested

Under the NASA Johnson effort, two different manufacturers were employed to build two different size tanks. One, built by Martin Marietta (MM) (fig. 1), was sized for a 30 min rated duration breathing system and the other, built by Structural Composites Industries (SCI) (fig. 2), was sized for a 45 min rated duration system. Both tanks were cylinders with aluminum liners and glass fiber/epoxy composite overwrap. References 3 and 4 contain the details of the MM and SCI development programs.

The MM vessel had an outside diameter of 5.60 in and an overall length of 18.6 in. The contained volume was 283.2 in^3 (unpressurized) which was equivalent to 41.5 SCF of air at 4000 psi and 70 °F. The maximum operating pressure was 4500 psi, sizing pressure was 7600 psi, proof pressure 6500 psi, and the minimum guaranteed burst was 9000 psi. Bottles taken on a single cycle to burst failed at an average of 13 200 psi. The not-to-exceed design weight was 9.0 lb, and the actual as manufactured weight averaged 8.3 lb.

The SCI vessel had an outside diameter of 6.5 in and an overall length of 19.2 in. The contained volume was 412 in^3 (unpressurized) and provides for containment of about 61 SCF of air at 4000 psi and 70 °F. The maximum operating pressure was 4500 psi, sizing and proof pressure were 6570 psi, and the minimum guaranteed burst pressure was 9000 psi. Most units subjected to burst testing failed at pressures above 13 000 psi. Finished weight of the bottles averaged 12.8 lb, 10 percent below the not-to-exceed design weight of 14 lb.

Load Sharing Liner Design

Both the MM and SCI pressure vessels were designed using the load sharing liner approach wherein the liner carries 1/4 to 1/3 the pressure load at the operating condition. The remainder of the pressure load is, of course, carried by the glass fiber composite reinforcement. Figure 3 presents the stress (or pressure) strain curve for a bi-element load sharing liner concept. As can be seen from figure 3, during the proof-pressure cycle of the pressure vessel, the metal liner is strained plastically while the glass filaments are strained elastically. Upon subsequent release of pressure, the liner material, which has now taken a permanent set, is forced into compression by the filaments trying to return to their original position. Since the proof-pressure cycle plastically deforms or "resizes" the liner, it is referred to as the "sizing" cycle. Subsequent cycles to the operating pressure produce loads that can be carried completely within the elastic capabilities of both the glass filaments and liner material. For the MM and SCI vessels, the specific design pressures and structural operating conditions are shown in table I.

Materials used by SCI were 6351-T6 aluminum for the liner, 20 end S-2 glass roving (Owens Corning), and a resin system of DER-332 (DOW Chemical)/-hexahydrophthalic anhydride/BDMA; 100/84/0.5 pbw. The filament winding was a wet process, and cure was 16 hr at 300 °F. For the MM vessels, the liners were 6070-T6 aluminum. As with SCI, 20 end S-2 glass roving was used in a wet filament winding process. MM, however, used a resin system composed of Epon 828/Epon 1031/nadic methyl anhydride/BDMA; 50/50/90/0.5 pbw. Cure for this resin system was 3 hr at 330 °F. Both manufacturers used an interspersed winding pattern where layers of hoop filaments were alternated with layers of longitudinal filaments instead of wrapping all the longitudinals and then all the hoop layers. Both manufacturers also used a seamless liner with a hot swage forming operation to close out the open end (boss) of the cyclinder. SCI used a deep draw operation to form the cylinder while MM used an impact extrusion process.

Test Facility

The NASA Lewis test facility consisted of three elements; the environmental exposure rack, a pressure cycling rig, and a burst test rig. A brief description of each of these elements is as follows.

Environmental exposure. - To provide long term exposure of pressurized equipment to the outdoor environment, a fenced in pad area was available in a controlled access hazardous test area. Figure 4 shows the pad, with racks and bottles in place. As can be seen, there are eight racks with space on most racks for up to five pressure vessels. Each rack of bottles was supplied hydraulic oil pressure from a separate accumulator. Accumulators, pressure gages and transducers, and monitoring equipment were all contained within a temperature controlled (70±10 °F) trailer. Individual bottle pressures were not monitored, but all the bottles on a rack were considered to be equal to their respective accumulator pressures which were monitored twice a day (3 a.m. and 3 p.m.). For the first 3 yr, a temperature probe attached to one bottle was operational and was recorded along with the pressure data. Recorded temperatures varied from ±110 °F in the direct sun during the hottest days of summer to -15 °F in the coldest nights of winter. Because of the environmental exposure, however, the temperature probe stopped functioning, and during the latter years no temperature information was available. Initially, data was recorded with a multipoint strip chart recorder and an alarm function was provided by pressure switches on each accumulator. Midway in the program, a data logger with internal alarms was installed and operated without problems for the balance of the test program. Alarms, which were set to activate if the pressure was above 4500 psi or below 4000 psi, were both audible and visual in the control room for the test area but did not cause any adjustment in pressure. With this system it was possible to maintain the pressure fairly well within the 4000 to 4500 psi limits with seasonal adjustment of the accumulator. Short duration spikes to 4700 psi on the high side and 3800 on the low side were occasionally experienced during weekends and holidays when personnel were not available within the control room to monitor alarms and correct for environmentally induced pressure changes.

Pressure cycling rig. Some of the bottles were removed yearly and pressure cycled in another test facility. A simplified schematic of the pressure cycling rig (PCR) is seen in figure 5. Basic components of the PCR were a high volume air-operated hydraulic pump, a 1-gal accumulator, a servovalve (controlled by an analogue programmer), and a transfer piston. Operation of the PCR was controlled by a Datatrak which was programmed to position the servovalve in response to a comparison between the preset pressure cycling ramp rates and the actual tank pressure as indicated by the pressure transducer signal. An accumulator was used in the system to eliminate pressure spikes from the pump, to smooth the tank pressurization profile, and to ease the burden on the pump. Cleanliness of the oil in the pump was a critical item for dependable operation and a closed hydraulic system was required. Therefore, a transfer piston was placed between the pressure vessel to be tested and the pump. Appropriate limit switches were installed in the system to shut down the pump should an out of tolerance pressure (or cycle time) be detected. Up to four pressure vessels could be tested simultaneously and cycle rates, which depended on the total volume expansion of the tank(s) being tested, typically ranged from 2 to 5 min/cycle. The PCR was able to run in an unattended mode and a 1000 cycle test usually took less than a week. During the cycle test program, tank pressures were recorded on a strip chart recorder.

Burst test rig. The burst test rig (BTR) was a very simple facility. A 20 000 psi pump and throttle valve were located in the control room and separated by a blast wall from the test tank, pressure gage, and pressure transducer. The test tank and pressure transducer were further enclosed in a steel container which prevented damage from projectiles which might result from the burst and also prevented the hydraulic oil from being sprayed directly into the blast room. A steel plate baffle in the blast container prevented damage to the transducer which was close coupled (6 in) to the test tank pressure inlet. A pressure gage, outside of the blast container, was used to verify the calibration of the transducer and provide a redundant pressure measurement. Output from the pressure transducer was recorded on a strip chart in the control room.

DISCUSSION OF RESULTS

During the period from January 1974 thru January 1985, 29 Martin Marietta and 7 Structural Composites Industries pressure vessels were tested. All of these tanks were as-wound and had no protective paint or exterior coating. Table II lists all the vessel serial numbers and the pertinent test data. Three of the 29 MM tanks failed on the test rack during the test period. SN 77 which had been under continuous pressure between 4000 and 4500 psi failed after 6.8 yr due to a crack in the liner eminating from a fold line in the hemisphere on the boss end. Fold lines had been a problem in many of the early liners and leakage failure during cycling was not uncommon. SN 72 which had seen 3000 pressure cycles from 100 to 4500 psi also failed due to liner leakage while on the environmental exposure rack (EER) at 4500 psi. Cause of the SN 72 failure was a deep pit in the liner hemisphere on the closed end. The cause of the pitting is unknown and no other tank has shown any evidence of pitting. SN 77 and SN 72 were both slow leakage type failures with no damage to the glass fiber composite. SN 44, however, failed due to fiber rupture while under pressure on the EER. SN 44 had seen 7000 cycles from 100 to 4500 psi in addition to approximately 8.5 yr exposure on the EER and was the only tank to fail due to stress rupture of the composite. Since there was no evidence of any physical damage which could have caused the failure, it can only be surmised that the combination of many operating cycles and long time under load brought the composite to the end of its useful life. Further discussion of this data point will be found in paragraph three, below.

Environmental Effects - Tank Performance

The outdoor environment of Cleveland, Ohio was deleterious to the physical condition of the unprotected pressure vessels. Loss of resin from the outer plies of the fiberglass was experienced by all bottles that had more than a few years of exposure. Figure 6 shows one of the SCI bottles after 10 yr exposure, and the extent of the exterior degradation is evident. The effects of the exposure were, however, somewhat variable. Some vessels would show almost 100 percent surface erosion and extensive fraying of the exposed glass fibers while other would have only localized circumferential bands that seemed to be affected.

(1) Unpressurized vessel performance: The trend of the outdoor exposure was to reduce performance, but the performance of the pressure vessels seemed to bear no correlation to the amount of surface damage. As can be seen in figure 7, unpressurized vessels (composite stress at 13 to 14 percent of

ultimate) that were stored indoors, experienced an 11 percent degradation in performance. Unfortunately, this was based on a limited number of tests. Vessels of both types were tested after 1 yr of fire department service which was basically an indoor storage. A single MM vessel (SN 4-30) which had been in an uncontrolled indoor storage at NASA Johnson was tested 5 yr after manufacture, and a similar vessel was tested 10 yr after manufacture. In the case of bottles exposed to the environment, a significant degradation trend is evident in figure 7 even though there also appears to be significant data scatter. The vessel that was tested after 3 yr exposure, MM 16, showed a 30 percent reduction in burst strength while MM 37 (4 yr) and MM 76 (6 yr) only experienced a 23 percent reduction in burst strength. Even MM 48 which was tested after 10 yr of unpressurized exposure only exhibited a 28 percent degradation in performance. In any case, the performance of the exposed bottles was degraded, perhaps by as much as 30 percent over a 10 yr period as compared to the 11 percent degradation for bottles which were stored indoors.

(2) Pressurized vessel performance: Effects of environmental exposure under pressure (composite stress at 31 to 32 percent of ultimate) were even more severe than in the zero pressure case. Figure 8 is a plot of 12 bottles tested over the 10 yr period, and it can be seen that there is significant scatter in the data. If only the first 5 yr of data are considered, the data group very nicely and show a severe drop in performance: 10 percent per year degradation in burst pressure. However, after 5 yr, the remaining six data points show a maximum reduction of strength of 30 percent and are fairly consistent at that level. Since there is no physical phenomena which would account for the pressure vessels regaining strength with additional years of exposure, the data trend can only be caused by the variability of the effect of the environment and/or by the variability of the as-manufactured pressure vessels. A linear regression analysis on the pressurized, exposed data yields the solid line shown on figure 8, but the correlation coefficient, R^2, has a value of only 0.4243 and thus the curve fit is not precise. A 35 to 50 percent degradation at 10 yr exposure appears to be a realistic projection based on the data, although a straight line projection may be unconservative in the early years.

(3) Pressurized and pressure cycled vessel performance: As might be expected, the most severe effect of the environment was on vessels which were subjected to pressure cycling once a year and held at constant pressure the remainder of the time. The pressure cycling required taking the bottles off the EER and installing them in the PCR. Depending on the number of bottles being cyclically tested, the process could take from 2 to 4 weeks before the bottles were back in the EER. The actual time to perform one pressure cycle varied from 1 to 5 min so the time required for the 1000 cycle block actually took from 1 to 3 days (round the clock operation). A block of 1000 pressure cycles was completed once a year on these bottles, and the resulting burst pressure data is shown in figure 9. This data is nicely behaved in that it fits a liner regression analysis curve with a correlation coefficient, R^2, of 0.917. Unfortunately, the trend is toward a degradation of 6-1/2 to 7 percent per year, such that after 10 yr of exposure (10 000 operating cycles), the vessels would have only 30 to 35 percent of the ultimate strength remaining. The fact that bottles which were pressure cycled seemed to be affected to a greater degree by the environment that bottles which were not pressure cycled is probably due to the increased amount of resin cracking and crazing which occurs with each pressure cycle. Each of the cracks is a point of attack for water and contaminates carried by the environment. Figure 10 is a photo of MM

44 which had seen 7000 pressure cycles from about 100 psi to 4500 psi and had been exposed to the environment for 8.5 yr under a constant pressure of 4500 psi. As can be seen, the surface effects due to the environmental exposure of this bottle are less severe than other bottles with equivalent (or longer) times of exposure. Since MM 44 experienced the most severe degradation of any vessel tested, it can then be inferred that the subsurface effects of moisture (or other contaminates) introduced through the resin craze lines are both less visible and more severely damaging than surface erosion.

Composite performance. - Assuming that the pressure vessel failures where fiber rupture occurred (not a liner leak) were initiated by failure of the composite, it was possible to calculate the composite stress at failure and plot composite degradation as a function of pressure history and environmental exposure. This can be seen in figure 11 and shows that, by comparison to figure 9, the degradation of the composite is more severe than the degradation of the pressure vessel. While this may seem obvious, two items should be noted. First, the premise that the pressure vessel failure is controlled by composite failure is a sound assumption, especially at low pressure. MM 71 demonstrated that a liner flaw which would cause failure at 5100 psi did not result in fiber failure. And, second, while considerable scatter still is seen in the data, the one vessel that actually failed under sustained load of 31 percent of ultimate at 8-1/2 yr is not too far below that which would be projected by Chiao, et al. (ref. 5). Figure 12, which is taken from R5, shows the expected failure curves of glass epoxy composites tested in the relatively benign environment of 72 to 82 °F with RH at 24 to 37 percent. With this environment, there was a 1 percent chance of failure in 10 yr at a sustained load equal to 33 percent of the reference ultimate fiber strength. For the pressure vessels reported herein, temperatures during testing ranged from -15 to +110 °F and humidities varied from 30 percent to 100 percent. In addition, there was exposure to UV radiation. Consequently, the degradation experienced by the unprotected fireman's backpack bottles should not be considered to be unexpectedly severe. It is believed that coatings and paints exist which will eliminate the environmentally induced damage to the composite and hence the pressure vessels. To demonstrate the effectiveness of these coatings, a series of pressure vessels have been under test since February 1980, and the limited data to date indicates no degradation is occurring. The coated vessel test program will run through the year 1990. Coatings will not, however, eliminate the long term sustained load effects of glass fiber composites. Thus, pressure vessel design must apply the data generated by Chiao et al. as presented in reference 5 (and by various other researchers) to develop conservative operating characteristics and a realistic design life. That this can be done effectively is best exemplified by the fact that SCI has now built over 100 000 pressure vessels using the load bearing liner concept and, to date, none of these have experienced premature fiber failure due to environmental or stress corrosion effects.

CONCLUSIONS

Exposure of uncoated glass epoxy composites to the varying environment of Cleveland, Ohio resulted in a degradation of the composite strength. The environmental effects were variable and did not correlate with visual surface effects. Worst case degradation was, however, only slightly greater than would be predicted for a benign laboratory environment (constant temperature and low humidity with no UV).

RECOMMENDATIONS

It is recommended that the ongoing test program with coated fiberglass pressure vessels be continued and the results be compared with the uncoated test data to verify the capability of the coatings in preventing degradation due to environmental effects.

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4. King, H.A.; and Morris, E.E.: Improved Fireman's Compressed Air Breathing System Pressure Vessel Development Program. (SCI-7338, Structural Composites Industries; NASA Contract NAS9-12414.) NASA CR-134385, 1973.

5. Chiao, T.T., et al.: Stress-Rupture of Simple S-Glass/Epoxy Composites. J. Compos. Mater., vol. 6, no. 3, July 1972, pp. 358-370.

TABLE I. - DESIGN PRESSURES AND STRESSES FOR FIREMAN'S BREATHING SYSTEM PRESSURE VESSELS

	Manufacturer	
	Structural Composites Industries	Martin Marietta
Pressure, psi		
Proof	6 750	6 750
Operating	[a]4 000 at 200 °F	4 500 at 70 °F
Burst (avg. actual)	14 000	13 000
Burst (min. guar. design)	9 000	9 000
Stresses, psi		
Liner (max.)		
"0" pressure	-35 218	-28 400
Proof	41 967	46 200
Operating	22 550 (22 547 at 75 °F)	28 300
Burst (9000 psi)	50 712	53 600
Hoop composite		
"0" pressure	38 606	38 800 (fiber)
Proof	112 752	102 700
Operating	87 293 (82 544 at 75 °F)	79 800
Burst (9000 psi)	164 709	142 200
Longitudinal composite		
"0" pressure	22 092	25 000
Proof	63 027	62 500
Operating	56 064 (42 977 at 75 °F)	50 000
Burst (9000 psi)	100 709	110 500

[a]SCI designed their pressure vessel for 4000 psi at 200 °F as opposed to Martin who used 4500 psi at 70 °F.

TABLE II. - TEST DATA SUMMARY

Bottle style	Serial number	Pre-burst history	Years of exposure	Burst pressure	Comments
SCI	42	As MFG	0	14 200	
SCI	71	1 yr Fire Dept. Ser.		14 100	
SCI	56	1 yr Fire Dept. Ser.		13 900	
SCI	57	Same + 10 000 cy to 4000 psi		12 500	
SCI	72	Same + 10 000 cy to 4000 psi		14 050	Liner fold crack
SCI	55	4250 psi continuous	10	10 000	
SCI	67	Zero pressure	10	12 150	
MM	4-37	1 yr Fire Dept. Ser.	0	13 300	
MM	4-33	1 yr Fire Dept. Ser.		13 200	
MM	4-60	Same + 2 cy to 5000 psi		13 300	
MM	4-6	Same as 4-33 + 9000 cy to 4000 psi		13 100	
MM	4-20	Same as 4-6		10 700	
MM	4-30	5 yr uncontrolled indoor		12 600	
MM	4-42	10 yr uncontrolled indoor		11 600	
MM	8	4250 psi continuous	1	10 600	
MM	62		2	11 700	
MM	30		3	10 000	
MM	39		4.1	9 100	
MM	20		4.3	8 270	
MM	67		5	6 600	
MM	17		6	9 400	
MM	77		6.8	4 500	Liner leak
MM	29		7	9 700	
MM	46		7	9 200	
MM	45		8	9 300	
MM	71		9	5 100	Liner leak
MM	66		10	9 900	
MM	73	Same + 2000 cy to 4500 psi	2.1	10 500	
MM	68	Same but 3000 cy	4	11 080	
MM	72	Same as 68	4.3	4 500	Liner leak
MM	27	Same as 68 but 5000 cy	6	8 700	
MM	44	Same as 68 but 7000 cy	8.5	4 500	Fiber failure
MM	16	Zero pressure	3	9 200	
MM	37		4	10 200	
MM	76		6	10 200	
MM	48		10	9 600	

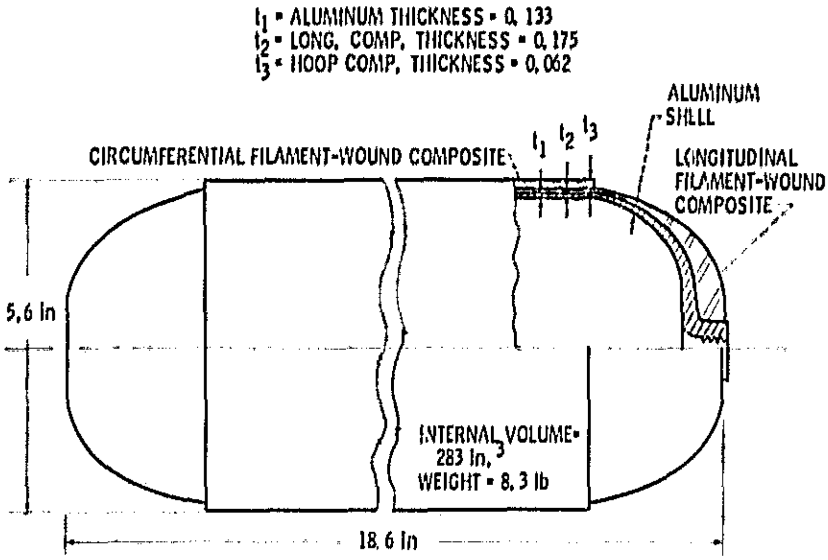

Figure 1. - Dimensional details of Martin Marietta composite pressure vessel for a fireman's backpack system.

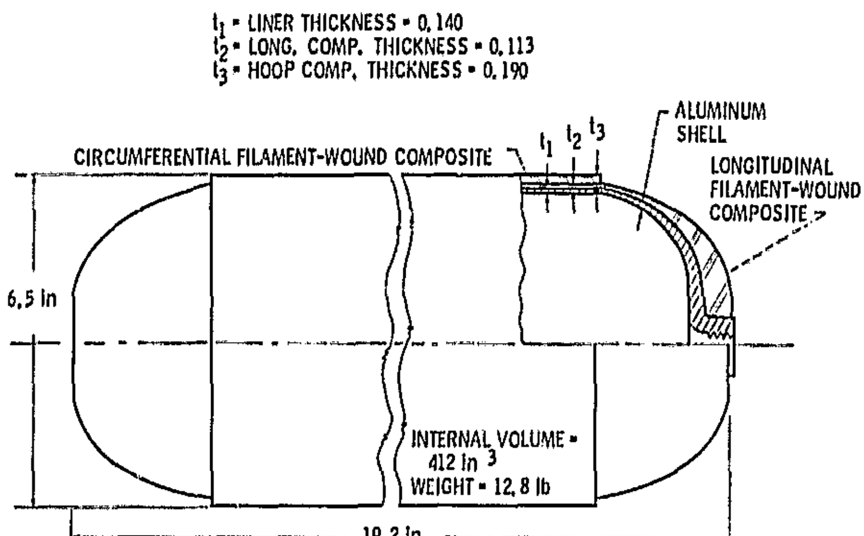

Figure 2. - Dimensional details of Structural Composites Industries composite pressure vessel for a fireman's backpack system.

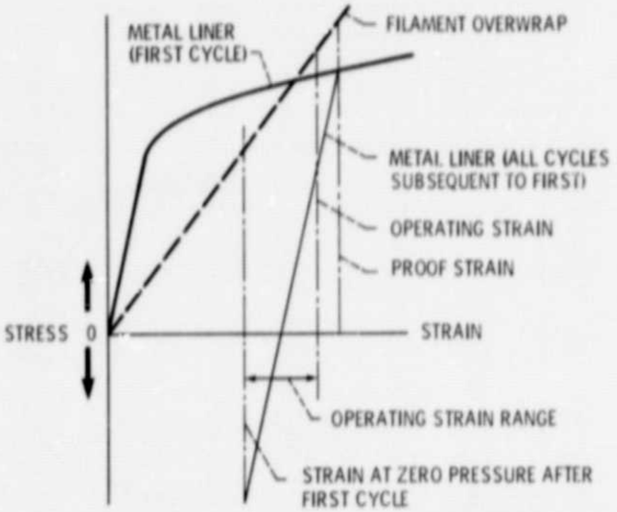

Figure 3. - Stress-strain curve for filament-overwrapped metalic pressure vessels.

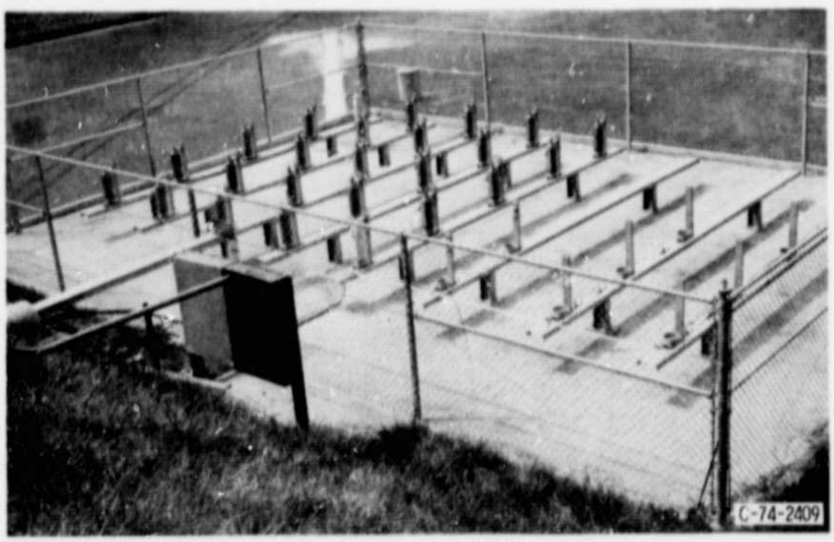

Figure 4. - NASA LeRC Environmental Exposure Facility.

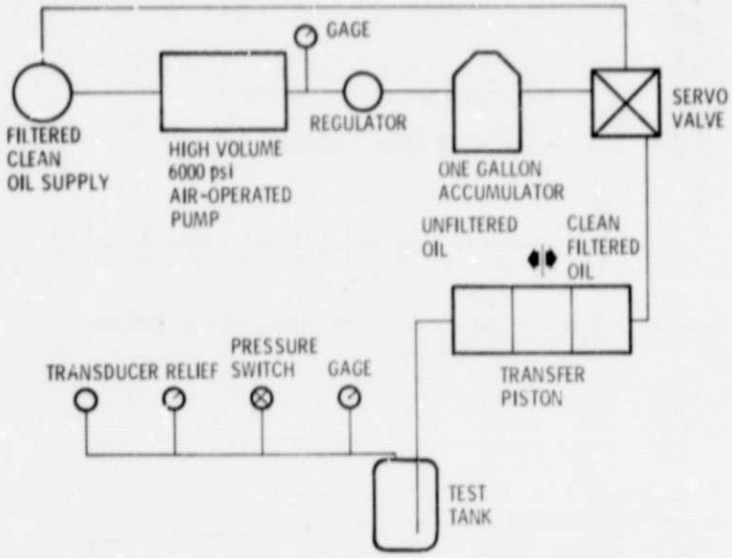

Figure 5. - Simplified schematic of pressure vessel , Pressure Cycle Test Rig.

Figure 6 SCI fireman's pressure vessel after 10 years exposure to outdoor environment.

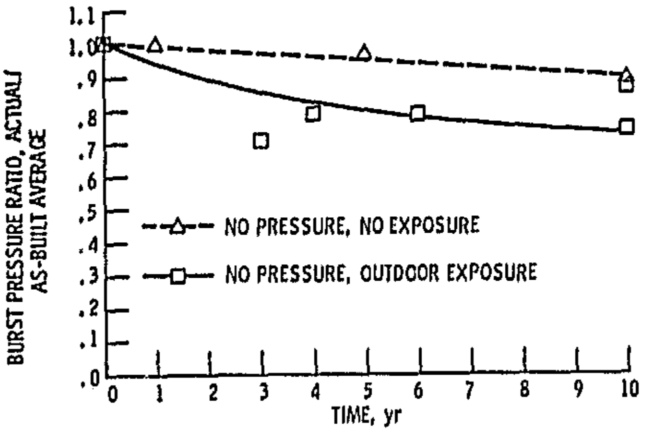

Figure 7. - Effect of environmental exposure on glass fiber composite pressure vessels.

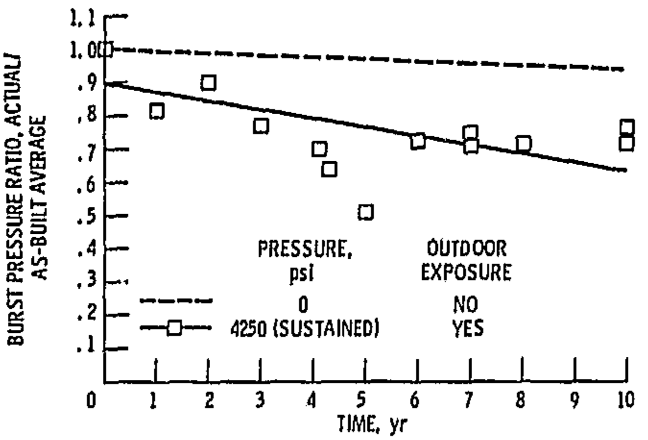

Figure 8. - Effect of sustained load and outdoor environment on glass fiber epoxy composite pressure vessels. (Martin Marietta design.)

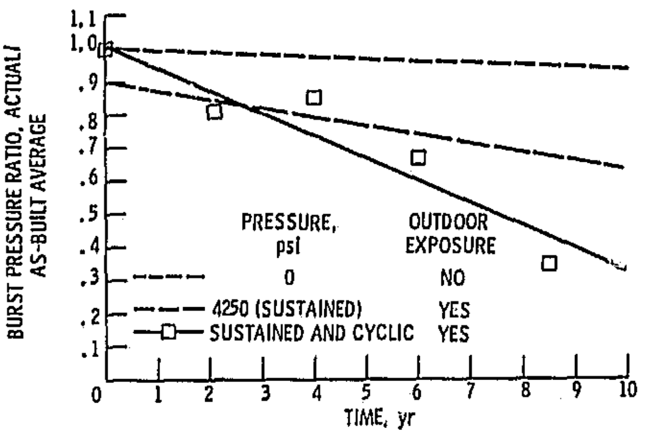

Figure 9. - Effect of stained and cyclic loads and outdoor environment on glass fiber/epoxy composite pressure vessels. (Martin Marietta design.)

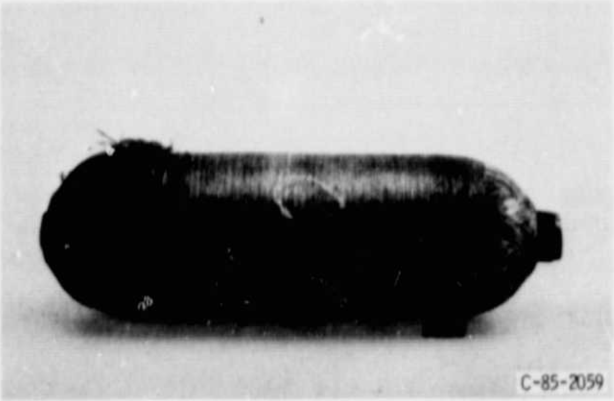

Figure 10. - Martin Marietta fireman's pressure vessel after 8 1/2 years of exposure and 7000 pressure cycles.

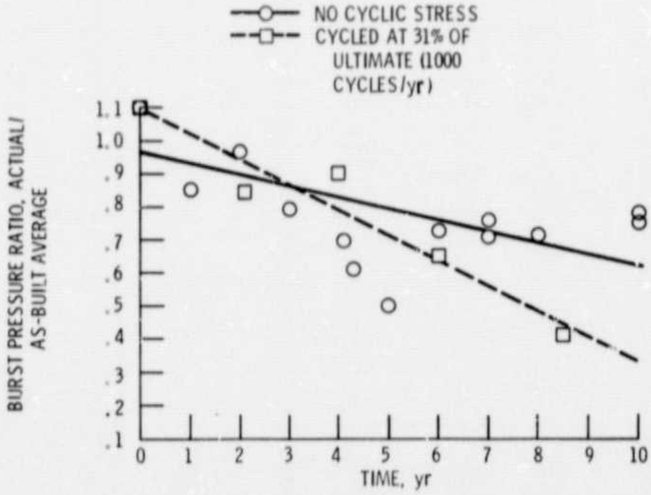

Figure 11. - Effect of sustained and cyclic loads and outdoor exposure on glass fiber epoxy composites. (Sustained load stress equaled 31 percent of original ultimate for all tests.)

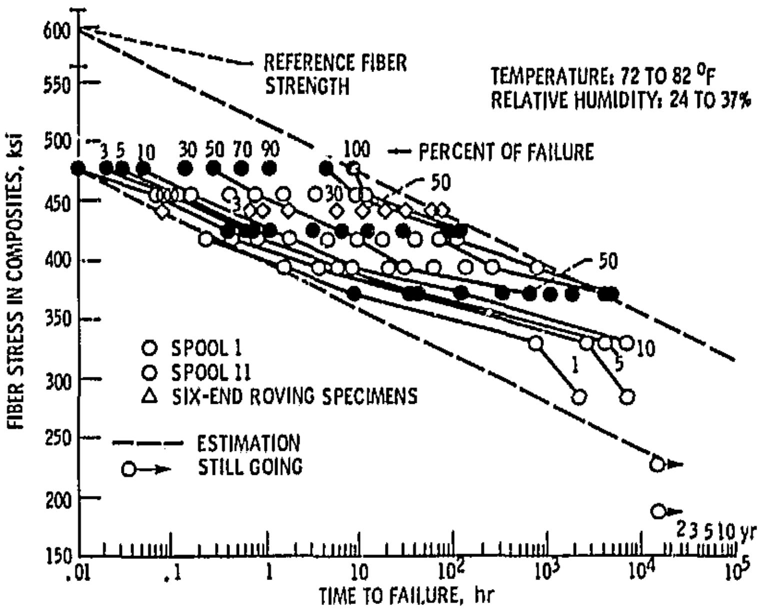

Figure 12.- Failure contour lines of simple S-glass/epoxy composites.

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15. Supplementary Notes

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16. Abstract

By the beginning of the 1970's composite pressure vessels had received a significant amount of development effort, and applications were beginning to be investigated. One of the first applications grew out of NASA Johnson Space Center efforts to develop a superior emergency breathing system for firemen. While the new breathing system provided improved wearer comfort and an improved mask and regulator, the primary feature was low weight which was achieved by using a glass fiber reinforced aluminum pressure vessel. Part of the development effort was to evaluate the long term performance of the pressure vessel and as a consequence, NASA JSC procured some 30 bottles for a test program. These bottles were then provided to NASA Lewis Research Center where they were maintained in an outdoor environment in a pressurized condition for a period of up to 10 yr. During this period, bottles were periodically subjected to cyclic and burst testing. There was no protective coating applied to the fiberglass/epoxy composite, and significant loss in strength did occur as a result of the environment. Similar bottles stored indoors showed little, if any, degradation. This report contains a description of the pressure vessels, a discussion of the test program, data for each bottle, and appropriate plots, comparisons, and conclusions.

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